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Energetic and exergetic assessment of the industrial sector at varying dead (reference) state temperatures: A review with an illustrative example

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Abstract

One of the keystones for obtaining sustainable development is the use of exergy analysis. The present study deals with the assessment of energy and exergy utilization efficiencies in the industrial sector. Attempts have also been made at understanding the effect of varying dead (reference) state temperatures on these efficiencies. In this context, the methodology used is presented first. It is then applied to Turkey, which is selected as an application country, based on the actual data for 2003. Finally, the results obtained are evaluated and discussed. The Turkish industrial sector (TIS) considered includes iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, non-iron metal industry and others such as textile and yarn, glass and glassware production, paper, beverage and cigarette, food, wood, leather, etc. All activities in this sector are produced by using electricity and heat energy. Parametric expressions of energy and exergy efficiencies are developed as a function of the dead-state temperature. The energy and exergy efficiency values for the TIS are found to vary from 51.95% to 80.82% and 25.30% to 29.50% at the dead-state temperature variations between 0 and 25 °C, respectively. It is expected that this study will be very beneficial in developing energy policies of countries from the exergy management point of view.

Keywords: Dead state; Energy efficiency; Exergy; Industrial sector; Sustainable development; Turkey

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Contents

1. Introduction

The energy balance is the basic method of process investigation. It makes the energy analysis possible, points at the needs to improve the process, is the key to optimization and is also the basis to developing the exergy balance.

1.1. Terminology of energy and exergy balances

Analysis of the energy balance results would disclose the efficiency of energy utilization in particular parts of the process and allow comparing the efficiency and the process parameters with the currently achievable values in the most modern installations. The analysis is using the concept of energy and its conservation. The forms of energy can be

Nomenclature

E	energy (kJ)
Ex	exergy (kJ)
IP	exergy improvement potential (kJ)
T	temperature (K)
a	share of energy use
e	share of electrical energy use
f	share of fuel use
Q	heat transfer (kJ)
q	quality factor of an energy carrier
R	correlation coefficient
R^2	coefficient of determination

Greek symbols

η	energy (first law) efficiency (%)
ε	exergy (second law) efficiency (%)
γ	exergy grade function

Indices

0	dead state or reference environment
c	component, cement
d	direct
e	electrical
f	fuel, first, fertilizer
h	heating, high
l	low
m	medium
o	overall
p	product
Q	heat
s	stream, sugar
is	iron and steel
ch	chemical
pc	petrochemical
oi	other industry

Abbreviation

TIS	Turkish industrial sector

expressed as enthalpy, internal energy, chemical energy, work, heat, electricity, etc. They will establish also the priority of the processes requiring consideration, either because of their excessive energy consumption or because of their particularly low efficiency. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change. Exergy is defined as the maximum work, which can be produced, by a system or a flow of matter or energy and it comes to equilibrium with a specified reference environment. Unlike energy, exergy is conserved only during ideal processes and destroyed due to irreversibilities in real processes [1].

The exergy concept was introduced to overcome limitations of the energy analysis. The exergy expresses the practical value of any substance (or any field matter, e.g., a heat radiation), and is defined as a maximum ability of this substance to perform work relative to human environment [2].

Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings. The available work that can be extracted from an energy source depends on the state of the source's surroundings. The greater the difference between the energy source and its surroundings, the greater the capacity to extract work from the system. The exergy analysis is the modern thermodynamic method used as an advanced tool for engineering process evaluation [3]. Whereas the energy analysis is based on the first law of thermodynamics, the exergy analysis is based on both the first and the second laws of thermodynamics. Also, Both analyses utilize the material balance for the considered system. Analysis and optimization of any physical or chemical process, using the energy and exergy concepts, can provide the two different views of the considered process.

1.2. Previous studies on evaluating sectoral energy and exergy utilization

The energy utilization of a country can be evaluated using exergy analysis to gain insights into its efficiency. The first one was applied by Reistad [4] to the US in 1970, while the most comprehensive one in terms of years appears to be Ayres et al.'s analysis of the US between 1900 and 1998 [5].

The approaches used to perform the exergy analyses of countries may be grouped into three types, namely first two approaches, Reistad's approach and Wall's approach, as denoted by Ertesvag and the last one Scuiba's approach [6].

The first approach considers flows of energy carriers for energy use, while the second one takes into account all types of energy and material flows. Reistad's approach was followed in the analyses of Finland [7], Canada [8], Brazil [9], the Organization for Economic Co-operation and Development (OECD) countries, non-OECD countries, and the world [10], England [11], and Saudi Arabia [12–15]. Besides these, the analyses of Ghana [16], Sweden [17], Japan [18], Italy [19] and Norway [20] followed Wall's approach. In addition, a new approach, the method of extended-exergy accounting (EEA), was introduced by Sciubba, and applied to the Italian society 1996 by Milia and Sciubba [21]. The EEA also assigns exergetic values (i.e. extended exergy, EE) to labor and to monetary flows within the system. In addition to that, Wall [22], Szargut [23] and Kotas [24] have performed most extensive studies in the exergy field. Szargut is the first scientist introducing the cumulative exergy consumption and cumulative degree of perfection for industrial processes and making the distinction between second law efficiency (exergetic efficiency or rational efficiency) and cumulative degree of perfection for industrial processes. However, Kotas

[24] has followed a similar approach giving different industrial processes such as sulfuric acid, gas turbine and refrigeration plants. Wall [22] presented the exergy flows for a pulp and paper mill and a steel plant by establishing the energy flows in processes and drawing up the exergy losses.

As for studies performed on Turkey's sectoral (commercial, residential, industrial and transportation) energy and exergy analyses, to date, 17 studies [5,25–40] were realized. Of these, 16 followed Reistad's approach, excepting to [26].

The methodology used in this study for analyzing Turkey's sectoral energy and exergy use is similar to that of Rosen and Dincer [27], who also used Reistad's approach with several minor differences. However, the effect of varying dead state temperatures on the energy and exergy utilization efficiencies in the industrial sector consists of the core of the present study.

1.3. Dead (reference) state definitions

In order to quantify the exergy of a system, we must specify both the system and the surroundings. The *exergy reference environment* is used to standardize the quantification of exergy. The exergy reference environment or simply the environment is assumed to be a large, simple compressible system. The temperature of the environment is assumed to be uniform at T_0, and the pressure is assumed to be uniform at P_0. In addition, it is assumed that any process does not significantly change the intensive properties of the environment. Some energy and exergy values are dependent on the intensive properties of the dead state. Consequently, the results of energy and exergy analyses generally are sensitive to variations in these properties. Before energy and exergy analyses can be applied with confidence to engineering systems, the significance of the delicateness of energy- and exergy-analysis results to reasonable variations in dead-state properties must be assessed. Actually, only a few analyses of dead-state variations have been reported. First, Wepfer and Gaggioli [41] have pointed out that exergy analyses of chemical plants are often relatively insensitive to variations in T_0 and P_0. Many have assumed that small and reasonable changes in dead-state properties have little effect on the performance of a given system.

Dead (reference) state definitions of exergy analysis have been studied by Krakow [42]. He reported that exergy analysis was an implicit comparison of the performance of real thermal systems with the performance of ideal, reversible thermal systems. Thermal power and refrigeration systems were considered to operate between high- and low-temperature reservoirs. Effective reservoirs temperature and specific humidity were defined to enable boundary conditions for real and ideal systems to be considered equivalent.

Gogus et al. [43] studied on the variation of environmental conditions in a process. In their study, the general exergy balance of a system was given based on the variation of the temperature of the surroundings. Using this balance, the mathematical equations regarding both the reversible work given to the system in the electric arc furnace used in a steel production and the exergy loss in the rotary burner used in a cement production were obtained.

Rosen and Dincer [44] investigated the effects on the results of energy and exergy analyses of variations in dead-state properties, and involved two main tasks, namely (i) examination of the sensitivities of energy and exergy values to the choice of the dead-state properties, and (ii) analysis of the sensitivities of the results of energy and exergy analyses of complex systems to the choice of dead-state properties. A case study of a coal-fired

electrical generating station was considered to illustrate the actual influences. The results indicated that the sensitivities of energy and exergy values and the results of energy and exergy ana1yses to reasonable variations in dead-state properties were sufficiently small that the findings, conclusions and recommendations based on such analyses usually were not significantly affected by the property variations.

Ozgener et al. [45] performed a parametric study using the actual operational data to investigate how varying dead-state temperatures from 0 to 25 °C affected the energy and exergy efficiencies of the Balcova geothermal district heating system in Izmir, Turkey and developed two significant correlations (with a correlation coefficient of 0.99) that could be used for predicting the efficiencies.

As for as parametric studies on varying dead-state temperatures on the sectoral basis are concerned, to the best of the authors' knowledge, energy and exergy utilization efficiencies in the Turkish residential–commercial sector have been investigated by Utlu and Hepbasli [6] for the first time. They comprehensively reviewed the studies performed in this field and also conducted a parametric study to investigate how varying dead-state temperatures ranging from 0 to 25 °C would effect energy and exergy utilization efficiencies in this sector.

In earlier studies conducted in this field, many authors used a dead-state temperature of 20 or 25 °C as a single value. The dead state is normally selected to be as similar to the accessible natural environment as possible. Usually P_0 and T_0 are selected to be 100 kPa and 273.15–323.15 K, and the chemical composition is taken to be similar to that of the accessible region of the crust of the earth.

Industrial sector accounts for about two-fifth of total final energy use in most countries. Energy consumption in the industrial sector depends mainly on the available amounts of local resources, which are closely connected with the present rural economy and industrializing. Fig. 1 illustrates energy and exergy flows in a macro system for the industrial sector including energy carriers and its subsectors.

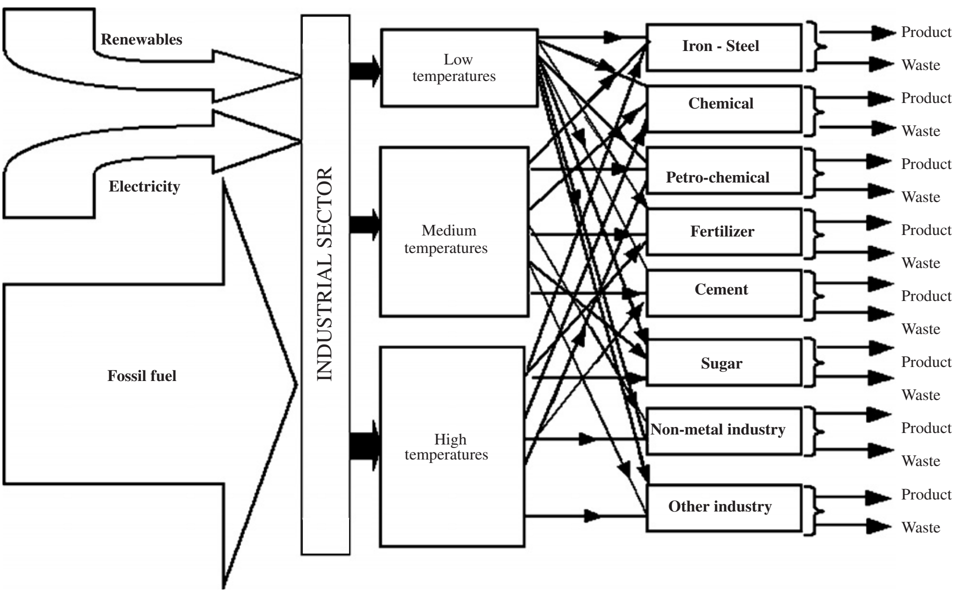


Fig. 1. An illustrative presentation of energy flows in the industrial sector for countries.

The primary objective of the present study is to conduct a parametric study of the effect of varying dead-state temperatures on energy and exergy utilization efficiencies of the industrial sector by presenting a case study based on the actual data. In this regard, thermodynamic relations used to perform energy and exergy analyses of dead-state variations are given first. Next, the obtained polynomial equations for the industrial and its subsectors such as iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, non-metal industry, and other industry are presented. These equations are then applied to the TIS. Finally, the results obtained are discussed.

2. Analysis

This section includes some of the key aspects of thermodynamics in terms of energy and exergy used in the modeling. Most relations, such as general energy and exergy balance equations, exergy associated with heat transfer and work, specific exergy, different ways of formulating exergetic efficiency, exergetic improvement potential, etc., used in the analysis may be obtained from Refs. [6,12], while some relations including quality factor, overall energy and exergy efficiencies, and exergetic improvement potential have been given in the following subsections.

2.1. Energy and exergy efficiency calculations in the industrial sector at varying dead-state temperatures

Industrial sector includes iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, and non-iron metal industry, other industry. All activities in this sector, by using electricity, and heat energy are produced.

Heating processes for each industry are grouped into low, medium, and high temperature categories as shown in Table 1. The temperature ranges given in this table are based on the work of Brown [1] and Dincer et al. [12]. The efficiencies for the low-, medium- and high-temperature categories are obtained from Reistad [4]. All mechanical drives are assumed to be 90% energy efficient.

The quality factors (or exergy grade function), q, for some energy carriers and forms have been listed elsewhere [12]. Quality of heat is Carnot factor that strongly depends on temperature, as stated in the following equation:

$$Q_{Carnot} = 1 - (T_0/T_p). \tag{1}$$

If fossil fuel is used, then exergy is as follows:

$$\mathrm{Ex} = Qq. \tag{2}$$

Energy efficiency is a simple comparison of energy content of input and output energy carrier or flow. However, energy efficiency is defined as a function of requirement temperatures in the system considered. Besides this, exergy efficiency is a simple comparison of exergy content of input and output energy carrier or flow. The exergy efficiency models obtained from this study are two order polynomial correlations because they are affected by different parameters of process in the industrial sector. Polynomial equations are calculated by using MATLAB Program. Energy and exergy efficiency values of these categories are determined separately.

Table 1
Process heating data and energy–exergy efficiency data for all categories of product heat temperature (T_p) in the industrial sector [1,4,12]

Industry	Breakdown of energy used each T_p (%)				Breakdown of energy efficiencies for each T_p category, by type	
	T_p range	Mean T_p (°C)	Electricity	Fuel	$\eta_{h,e}$	$\eta_{h,f}$
Iron and steel	Low	45	4.2	0	100.00	65.00
	Medium	0	0	0	90.00	60.00
	High	983	95.8	100	70.00	50.00
Chemical and petrochemical	Low	42	62.5	0	100.00	65.00
	Medium	141	37.5	100	90.00	60.00
	High	494	0	0	70.00	50.00
Petrochemical–feedstock	Low	57	0	0	100.00	65.00
	Medium	227	0	0	90.00	60.00
	High	494	0	100	70.00	50.00
Fertilizer	Low	57	10	30	100.00	65.00
	Medium	350	80	30	90.00	60.00
	High	900	10	40	70.00	50.00
Cement	Low	42	91.7	0.9	100.00	65.00
	Medium	141	0	9	90.00	60.00
	High	586	8.3	90.1	70.00	50.00
Sugar	Low	83	100	59	100.00	65.00
	Medium	315	0	9	90.00	60.00
	High	400	0	32	70.00	50.00
Non-iron metals	Low	61	10	13.8	100.00	65.00
	Medium	132	9.4	22.6	90.00	60.00
	High	401	80.4	63.6	70.00	50.00
Other industry	Low	57	10.6	13.8	100.00	65.00
	Medium	132	89.4	86.2	90.00	60.00
	High	400	0.1	0.1	70.00	50.00

2.2. Subsectors studied

In the following subsection, dead-state temperatures ranged from 273.15 to 298.15 K. Overall energy ($\eta_{ef,o}$) and exergy ($\varepsilon_{ef,o}$) efficiencies of these subsectors were calculated as follows:

$$\eta_{ef,o} = [(a_{ef,lh}\eta_{ef,lh}) + (a_{ef,mh}\eta_{ef,mh}) + (a_{ef,hh}\eta_{ef,hh})]/(a_{ef,lh} + a_{ef,mh} + a_{ef,hh}), \quad (3)$$

$$\varepsilon_{ef,o} = [(a_{ef,h}\varepsilon_{ef,h}) + (a_{ef,mh}\varepsilon_{ef,mh}) + (a_{ef,hh}\varepsilon_{ef,hh})]/(a_{ef,h} + a_{ef,mh} + a_{ef,hh}). \quad (4)$$

Energy efficiency values were obtained using relations given by Dincer [12]. By using actual system data and different dead-state values considered, two order polynomial correlations were obtained with higher coefficients of determination of R^2, as listed in Table 2. Figs. 3–8 show a variation of exergy efficiency values for the subsectors, which were briefly introduced below.

2.2.1. *Iron and steel industry*

This subsector is a major energy consumer in the industrialized country. Although it may show some deviations depending on these countries, in any industrialized nations, iron and steel industry accounts for 15–20% of the total industrial energy consumption, and 5–10% of the total primary energy consumption. In a typical iron and steel facility, major energy inputs include coal, electricity, natural gas, and fuel oil. Heating options specified for heating systems are electrical and fuel heating. Process heating data and energy efficiency data for all categories of product heat temperature in the iron and steel sector are shown in Table 1. Energy and exergy efficiencies of each heating categories considered for all system efficiencies are determined, and heating system and energy preference of process are determined according to their utilization ratios.

2.2.2. *Chemical–petrochemical industry*

Steam, electricity and by-products of some plants meet the required energy for the processes. Steam is the most important one having the biggest share, since it only supplies energy but also involves in many process. Various energy carriers such as natural gas, fuel oil and LPG are utilized in producing steam, which is mostly required under two different conditions. These are called low heating (316.15 K), and medium heating (414.15 K) as illustrated in Table 1. Electricity is used to obtain especially for electrolysis of salt and mechanical drive.

2.2.3. *Petrochemical–feedstock industry*

Steam, and by-products of some plants meet the required energy for the processes. Steam is the most important one and has the biggest share, since it supplies energy and is involved in many processes. Steam is mostly required under one condition, namely high heating, as illustrated in Table 1.

2.2.4. *Fertilizer industry*

Natural gas is the raw material and energy supplier for the fertilizer plants as well as ammonia. Steam and electricity are the other energy inputs. Other fertilizer plants normally use electricity for drives, compressors, and cooling. In case of additional energy requirement, low quality steam is generally utilized. Utilization categories of electricity and fuel energy are presented in Table 1.

2.2.5. *Cement industry*

The energy used in producing cement can be divided into two parts, namely electrical energy and thermal energy. Coal, lignite, fuel oil, or natural gas is used, as thermal energy resources, in order to require low, medium and high temperatures in the production of cement. Electricity is basically used to obtain mechanical drive at low and high temperatures in process.

Table 2
Exergy equations of subsectors in industrial sector

Industry	Heating options	Electrical energy		Fuel energy	
		Exergy equation	R^2	Exergy equation	R^2
Iron–steel	Low heating	$5.97484+0.314465T\ +8.33E{-}12T^2$	0.98	$3.88365+0.204403T{-}3.31E{-}18T^2$	0.98
	Medium heating				
	High heating	$53.3360+5.57E{-}02T+7.63E{-}12T^2$	0.98	$38.0971+3.98E{-}02T+1.53E{-}11T^2$	0.96
Chemical–petrochemical	Low heating	$5.07937+0.317460T{-}1.37E{-}12T^2$	0.96	$3.30159+0.206349T+6.11E{-}13T^2$	0.98
	Medium heating	$25.0000+0.217391T{-}1.28E{-}11T^2$	0.99	$16.6667+0.144928T{-}3.36E{-}12T^2$	0.96
	High heating	$42.7119+9.13E{-}02T+3.05E{-}12T^2$	1	$30.5085+6.52E{-}02T{-}1.50E{-}11T^2$	0.98
Petrochemical–feedstock	Low heating	$9.39394+0.303030T{-}4.58E{-}12T^2$	1	$6.10606+0.196970T{-}3.05E{-}13T^2$	1.00
	Medium heating	$36.18+0.18T{-}7.74E{-}17T^2$	0.98	$24.12+0.12T+2.15E{-}17T^2$	0.99
	High heating	$42.7119+9.13E{-}02T+3.05E{-}12T^2$	0.98	$30.5085+6.52E{-}02T{-}1.50E{-}11T^2$	0.96
Fertilizer	Low heating	$9.39394+0.303030T{-}4.58E{-}12T^2$	1.00	$6.10606+0.196970T{-}3.05E{-}13T^2$	1.00
	Medium heating	$46.8058+0.144462T{-}3.66E{-}12T^2$	0.98	$31.2039+9.63E{-}02T{-}3.36E{-}12T^2$	0.98
	High heating	$52.1569+5.97E{-}02T{-}3.66E{-}12T^2$	0.96	$37.2549+4.26E{-}02T+7.63E{-}12T^2$	0.98
Cement	Low heating	$3.30159+0.206349T+6.11E{-}13T^2$	1.00	$3.30159+0.206349T+6.11E{-}13T^2$	1.00
	Medium heating	$16.6667+0.144928T{-}3.36E{-}12T^2$	0.98	$16.6667+0.144928T{-}3.36E{-}12T^2$	0.98
	High heating	$32.5960+5.82E{-}02T{-}1.83E{-}12T^2$	0.99	$16.6667+0.144928T{-}3.36E{-}12T^2$	0.96
Sugar	Low heating	$16.0112+0.280899T+2.44E{-}12T^2$	1.00	$10.4073+0.182584T{-}3.11E{-}11T^2$	1.00
	Medium heating	$44.2347\ +0.153061T+3.66E{-}12T^2$	0.98	$29.4898+0.102041T{-}1.01E{-}11T^2$	1.00
	High heating	$38.9004+0.104012T{-}6.72E{-}12T^2$	0.97	$27.7860+7.43E{-}02T{-}1.83E{-}11T^2$	0.99
Non-iron metals	Low heating	$10.4752+0.300494T{-}5.11E{-}05T^2$	1.00	$6.81123+0.194652T{-}1.92E{-}06T^2$	1.00
	Medium heating	$23.5552+0.222331T{-}5.09E{-}06T^2$	0.98	$15.7042+0.148003T+6.78E{-}06T^2$	0.98
	High heating	$38.9466+0.103858T{-}1.16E{-}11T^2$	0.97	$27.8190+7.42E{-}02T{-}9.46E{-}12T^2$	0.96
Other industry	Low heating	$9.39394+0.303030T{-}4.58E{-}12T^2$	1.00	$6.10606+0.196970T{-}3.05E{-}13T^2$	1.00
	Medium heating	$23.5556+0.222222T{-}5.49E{-}12T^2$	0.98	$15.7037+0.148148T+5.19E{-}12T^2$	0.99
	High heating	$38.9004+0.104012T{-}6.72E{-}12T^2$	0.96	$27.7860+7.43E{-}02T{-}1.83E{-}11T^2$	0.96

2.2.6. Sugar industry

In this industry, energy utilization is required by means of electricity and fuel energy at low heating options, as shown in Table 1.

2.2.7. Non-iron metal industry

This industry consists of other metals such as manufacturing of fabricated metal products. Especially, electricity and fuel are used extensively in order to obtain high heat temperatures for product in this sector.

2.2.8. Other industries

Others industry includes textile and yarn, glass and glassware production, paper, beverage and cigarette, food, wood, leather etc. Especially, electricity and fuel are extensively used for medium categories of product heat temperatures.

2.3. Procedure for performing energy and exergy efficiency calculations in the industrial sector

In calculating overall energy and exergy efficiencies for the entire industrial sector, the following procedure was followed;

(a) Energy and exergy efficiencies were obtained in the process heating for each of the T_p categories.
(b) Mean heating energy and exergy efficiencies for the eight industries were calculated as follows:
- Weighted mean efficiencies for electrical heating and fuel heating were evaluated for each industry.
- Weighted mean efficiencies for all heating processes in each industry were evaluated with these values, using weighting factors as the ratio of the industry energy consumption (electrical or fuel) to the total consumption of both electrical and fuel energy.
- Values of energy and exergy utilization in the industrial sector were estimated according to energy carriers and subsectors. Total energy consumption in this sector was obtained from the relevant energy statistics and reports.

(c) Weighted mean overall (heating and mechanical drive) efficiencies for each industry were assessed using the weighting factor as the fractions of the total sectoral energy input for both heating and mechanical drives.

In the determination of sector efficiencies, weighted means for the weighted mean overall energy and exergy efficiencies for the major industries in the industrial sector were obtained, using the weighting factor as the fraction of the total industrial energy demand supplying to each industry:

$$\eta_{ote} = \frac{(\eta_{oe} e_{rc} + \eta_{of} f_{erc})}{(e_{rc} + f_{erc})}, \tag{5}$$

$$\varepsilon_{orc} = \frac{(\varepsilon_{oe} e_{rc} + \varepsilon_{1of} f_{exrc})}{(e_{rc} + f_{exrc})}. \tag{6}$$

Using the numerical values obtained from these models, the weighted mean overall energy and exergy efficiencies for the industrial sector were found.

3. An illustrative example

3.1. Energy and exergy utilization in the Turkish industrial sector

In earlier studies conducted on the energy and exergy analyses in the industrial sector, a dead-state temperature of 25 °C was used. The application presented here analyzes the energy and exergy utilization of the TIS based on variations of dead-state temperatures of process. In the analysis, the actual data for 2003 obtained from various sources were used [6,46,47].

Table 3
Energy and exergy inputs to the Turkish industrial sector during 2003

Energy carrier	toe/q[a]		Total input		Industrial sector inputs to sector	
			PJ	%	PJ	%
Hard coal	0.61	Energy	452.97	12.96	230.27	20.66
	1.03	Exergy	466.56	13.57	237.18	21.27
Lignite	0.21	Energy	404.82	11.58	87.90	7.89
	1.04	Exergy	421.01	12.24	91.42	8.20
Asphaltite	1.03	Energy	0.09	0.003	N/A	N/A
	0.97	Exergy	0.09	0.003	N/A	N/A
Petroleum	1.05	Energy	1346.06	38.50	283.53	25.43
	0.99	Exergy	1332.60	38.75	280.69	25.18
Natural gas	0.91	Energy	813.02	23.25	182.27	16.35
	0.92	Exergy	747.98	21.75	167.70	15.04
Wood	0.30	Energy	187.99	5.38	N/A	N/A
	1.05	Exergy	197.39	5.74	N/A	N/A
Biomass	0.23	Energy	52.29	1.50	N/A	N/A
	1.05	Exergy	54.91	1.60	N/A	N/A
Hydro-power	0.09	Energy	127.00	3.63	185.14	16.61
	1.00	Exergy	127.00	3.69	185.14	16.61
Geothermal (electric)	0.86	Energy	3.20	0.09	N/A	N/A
	1.00	Exergy	3.20	0.09	N/A	N/A
Geothermal (heat)	1.00	Energy	32.77	0.94	N/A	N/A
	0.29	Exergy	9.50	0.28	N/A	N/A
Solar	1.00	Energy	14.63	0.42	4.97	0.45
	0.93	Exergy	13.61	0.40	4.63	0.41
Wind	0.09	Energy	0.22	0.01	N/A	N/A
	1.00	Exergy	0.22	0.01	N/A	N/A
Coke	0.7	Energy	15.92	0.46	95.50	8.56
	1.05	Exergy	16.71	0.49	100.28	8.99
Petrocoke	0.77	Energy	45.16	1.29	45.16	4.05
	1.04	Exergy	47.87	1.39	47.87	4.29
Total		Energy	3496.15	100	1114.77	100
		Exergy	3438.66	100	1114.91	100

[a]The upper values are conversion factor to tons oil of equivalent (toe), while the lower values are quality factor.

The structures of Turkey's total, industrial sector and its subsectors as well as energy and exergy inputs for 2003 are listed in Table 3. As can be seen in this table, total energy and exergy inputs to the whole of Turkey were 3496.15 and 3438.66 PJ in 2003, respectively. Of total energy input, 28.34% was produced in 2003, while the rest will be met by imports. In 2003, production of 11 energy sources had the biggest share of the total coal including lignite and hard coal with 45.37%, followed by wood with 18.89%, hydropower with 12.75%, and petroleum with 10.47%. In 2003, renewable energy source production was the second biggest production source after total coal production, providing about 42% of the energy production.

In 2003, of Turkey's total end-use energy, 42% was used by the industrial sector, followed by the residential–commercial sector at 31%, the transportation sector at 19%, the agricultural sector at 4.8%, and the non-energy (out of energy) use at 3.2%.

The industrial sector of Turkey is composed of many industries, but the eight most significant industries are identified as iron–steel, chemical–petrochemical, petrochemical–feedstock, cement, fertilizer, sugar, non-metal industry, other industry. In order to simplify the analysis of energy and exergy efficiencies for this complex sector, energy consumption patterns are analyzed, and the eight most significant industries (in which the total energy consumption accounts for more than 95% of the total energy used in this sector) are chosen to represent the entire sector.

In the Turkish industrial sector, the energy used to generate heat for production processes accounts for 82% of the total energy consumption, with mechanical drives, lighting, and air-conditioning accounting for 18%. In the present study, it is decided to analyze the heating and mechanical end uses only. This simplification is considered valid since heating and mechanical processes account for 95% of the energy consumption in the industrial sector.

Heating processes for each industry are grouped into low, medium, and high temperature categories as shown in Table 1. Three steps are used to derive the overall efficiency of the sector as stated above. In the determination of sector efficiencies, weighted means for the weighted mean overall energy and exergy efficiencies for the major industries in the industrial sector are obtained, using the weighting factor as the fraction of the total industrial energy demand supplied to each industry. The efficiency calculations for a non-iron metal industry are shown in detail below.

3.2. Process heat efficiency calculations for the product heat temperature categories in each industry

Product heat data and exergy equations for each industry are separated into the categories defined in Tables 1 and 2. The resulting breakdown is shown in Table 4, with the percentage of efficiencies in each industry supplied by electricity and fossil fuels.

3.2.1. Electrical process heat calculations

In the non-iron metal industry, electric heating is used to supply low, medium, and higher heating categories of heat as shown in Table 4.

The energy efficiency for this end use is

$$\eta_{e,h} = Q_p / W_e = 1. \tag{7}$$

Table 4
Electrical and fuel heating exergy efficiencies values of the industrial sector at varying dead-state temperatures

Dead-state temperatures (K)	Iron–steel		Chemical–petrochemical		Petrochemical–feedstock		Fertilizer		Cement		Sugar		Non-iron metals		Other industry	
	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)	Electric ε_{oe} (%)	Fuel ε_{of} (%)
298	51.41	38.14	12.83	16.81	0.00	30.57	43.75	26.20	8.74	30.97	16.29	17.83	34.71	22.29	22.32	14.56
297	51.48	38.18	13.11	16.96	0.00	30.64	43.90	26.31	9.04	31.03	16.57	17.97	34.84	22.40	22.56	14.72
296	51.55	38.22	13.39	17.10	0.00	30.70	44.06	26.41	9.34	31.10	16.85	18.11	34.98	22.50	22.79	14.87
295	51.61	38.26	13.67	17.25	0.00	30.77	44.21	26.52	9.64	31.17	17.13	18.25	35.11	22.61	23.02	15.03
294	51.68	38.30	13.95	17.39	0.00	30.83	44.36	26.62	9.93	31.24	17.42	18.39	35.25	22.72	23.25	15.18
293	51.75	38.34	14.23	17.54	0.00	30.90	44.51	26.73	10.23	31.30	17.70	18.53	35.38	22.83	23.48	15.34
292	51.81	38.38	14.51	17.68	0.00	30.96	44.66	26.83	10.53	31.37	17.98	18.67	35.52	22.93	23.71	15.49
291	51.88	38.42	14.79	17.83	0.00	31.03	44.81	26.94	10.83	31.44	18.26	18.81	35.65	23.04	23.94	15.65
290	51.95	38.46	15.07	17.97	0.00	31.10	44.97	27.04	11.13	31.50	18.54	18.95	35.78	23.15	24.17	15.80
289	52.01	38.50	15.35	18.12	0.00	31.16	45.12	27.15	11.42	31.57	18.82	19.09	35.92	23.26	24.40	15.96
288	52.08	38.54	15.63	18.26	0.00	31.23	45.27	27.25	11.72	31.64	19.10	19.23	36.05	23.36	24.63	16.11
287	52.15	38.57	15.91	18.41	0.00	31.29	45.42	27.36	12.02	31.71	19.38	19.37	36.19	23.47	24.86	16.27
286	52.21	38.61	16.19	18.55	0.00	31.36	45.57	27.46	12.32	31.77	19.66	19.51	36.32	23.58	25.09	16.42
285	52.28	38.65	16.47	18.70	0.00	31.42	45.73	27.57	12.62	31.84	19.94	19.66	36.46	23.69	25.33	16.58
284	52.35	38.69	16.75	18.84	0.00	31.49	45.88	27.67	12.91	31.91	20.22	19.80	36.59	23.79	25.56	16.73
283	52.41	38.73	17.03	18.99	0.00	31.55	46.03	27.79	13.21	31.98	20.51	19.94	36.72	23.90	25.79	16.89
282	52.48	38.77	17.31	19.13	0.00	31.62	46.18	27.88	13.51	32.04	20.79	20.08	36.86	24.01	26.02	17.04
281	52.55	38.81	17.59	19.28	0.00	31.68	46.33	27.99	13.81	32.11	21.07	20.22	36.99	24.12	26.25	17.20
280	52.61	38.85	17.87	19.42	0.00	31.75	46.48	28.09	14.11	32.18	21.35	20.36	37.13	24.22	26.48	17.35
279	52.68	38.89	18.15	19.57	0.00	31.81	46.64	28.20	14.40	32.25	21.63	20.50	37.26	24.33	26.71	17.51
278	52.75	38.93	18.43	19.71	0.00	31.88	46.79	28.30	14.70	32.31	21.91	20.64	37.40	24.44	26.94	17.66
277	52.81	38.97	18.71	19.86	0.00	31.94	46.94	28.41	15.00	32.38	22.19	20.78	37.53	24.55	27.17	17.82
276	52.88	39.01	18.99	20.00	0.00	32.01	47.09	28.51	15.30	32.45	22.47	20.92	37.66	24.65	27.40	17.97
275	52.95	39.05	19.27	20.14	0.00	32.07	47.24	28.62	15.59	32.52	22.75	21.06	37.80	24.76	27.63	18.13
274	53.01	39.09	19.55	20.29	0.00	32.14	47.40	28.72	15.89	32.58	23.03	21.20	37.93	24.87	27.87	18.28
273	53.08	39.13	19.83	20.43	0.00	32.20	47.55	28.83	16.19	32.65	23.31	21.34	38.07	24.98	28.10	18.44

The exergy efficiencies for the three categories are

Low heating ($T_p = 334\,\mathrm{K}$):

$$\varepsilon_{e,h} = 10.4752 + 0.300494T - 5.11 \times 10^{-5}T^2,$$
$$\varepsilon_{e,h} = 10.4752 + 0.300494(288) - 5.11 \times 10^{-5} \times (288)^2$$
$$= 0.1377 \text{ (or 13.77\%)}.$$

Medium heating ($T_p = 405\,\mathrm{K}$):

$$\varepsilon_{e,mh} = 23.5552 + 0.222331T - 5.09 \times 10^{-6}T^2,$$
$$\varepsilon_{e,mh} = 23.5552 + 0.222331(288) - 5.09 \times 10^{-6} \times (288)^2$$
$$= 0.26 \text{ (or 26\%)}.$$

High heating ($T_p = 674\,\mathrm{K}$):

$$\varepsilon_{e,hh} = 38.9466 + 0.103858T - 1.16 \times 10^{-11}T^2,$$
$$\varepsilon_{e,hh} = 38.9466 + 0.103858(288) - 1.16 \times 10^{-11} \times (288)^2$$
$$= 0.409 \text{ (or 40.90\%)}.$$

Similarly, the exergy efficiencies for the other industries of process heating can be found using the same method of calculations. The results are presented in Figs. 2–9.

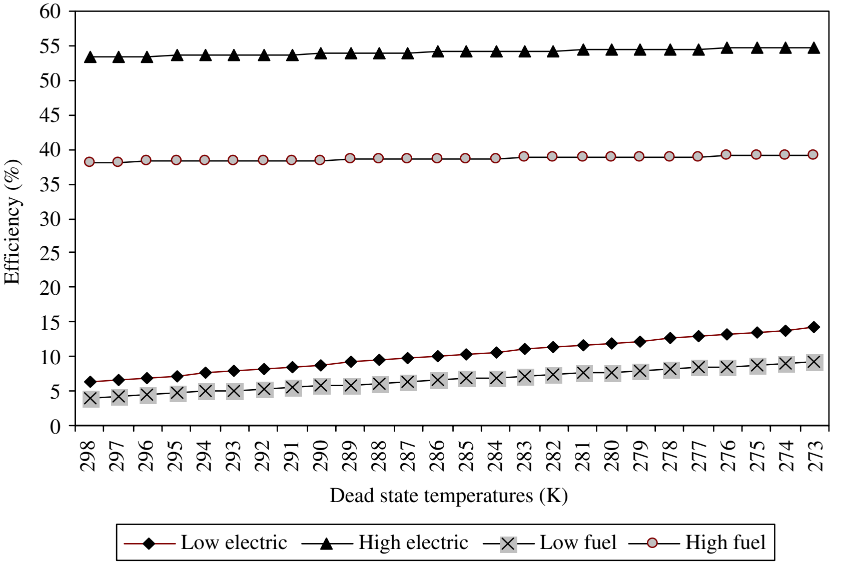


Fig. 2. Variation of exergy efficiencies for the iron–steel industry at various dead-state temperatures.

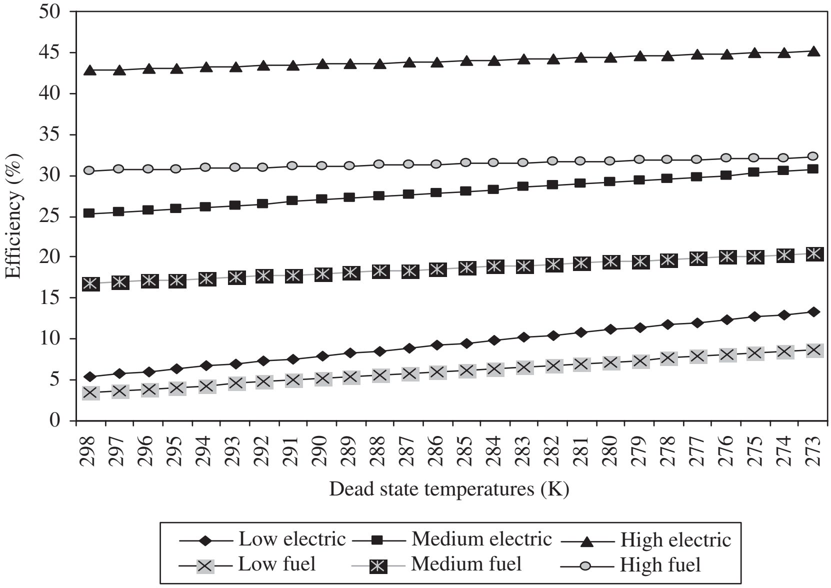


Fig. 3. Variation of exergy efficiencies for the chemical–petrochemical industry at various dead-state temperatures.

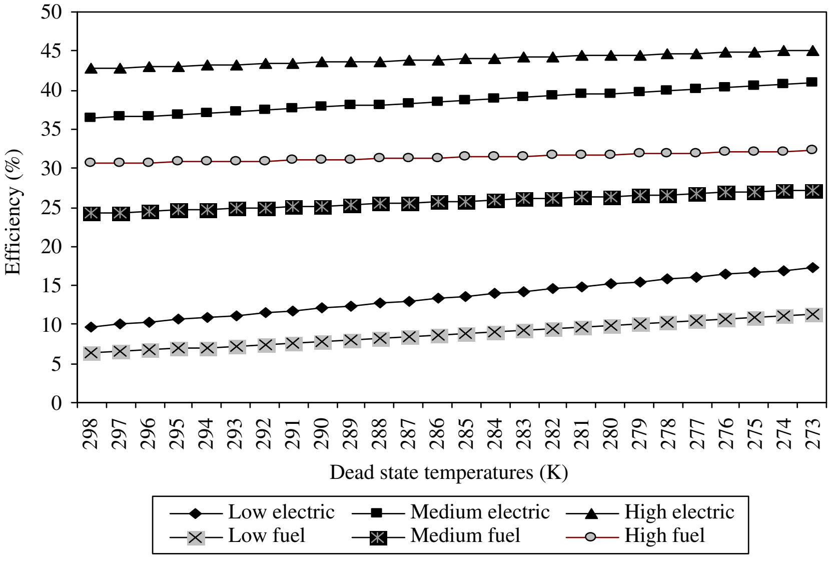


Fig. 4. Variation of exergy efficiencies for the petrochemical–feedstock industry at various dead-state temperatures.

3.2.2. Fossil fuel process heat calculations

The non-iron metal industry requires fossil fuel heating at all ranges of temperatures as given in Table 1. The energy efficiency for the low-temperature heating process is found to

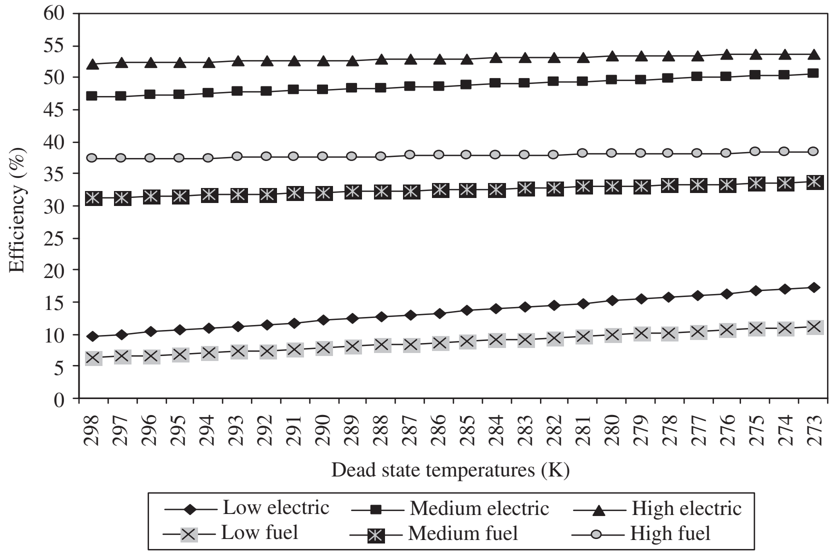


Fig. 5. Variation of exergy efficiencies for the fertilizer industry at various dead state temperatures.

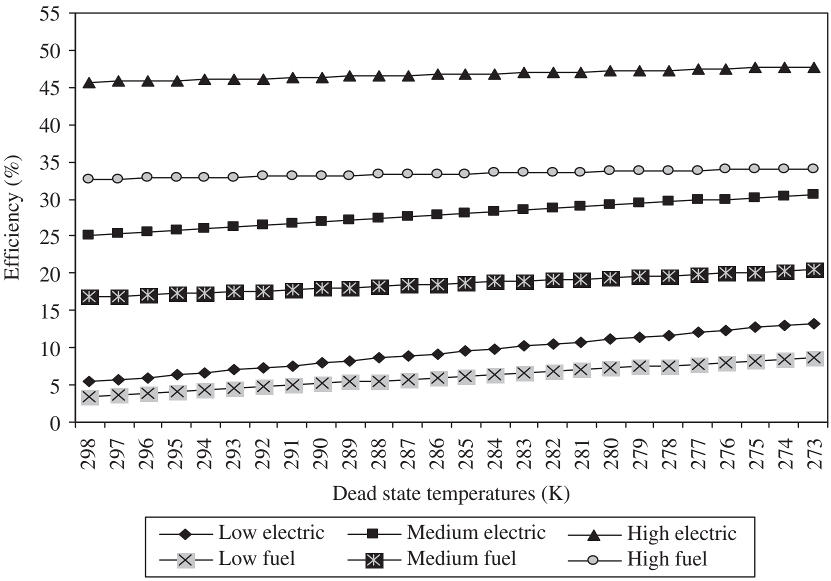


Fig. 6. Variation of exergy efficiencies for the cement industry at various dead-state temperatures.

be 0.65 (or 65%) using the following equation:

$$\eta_{f,h} = Q_p/m_f H_f. \tag{8}$$

Similarly, the energy efficiency for the medium- and high-temperature heating process are found to be equal to 60% and 50%, respectively.

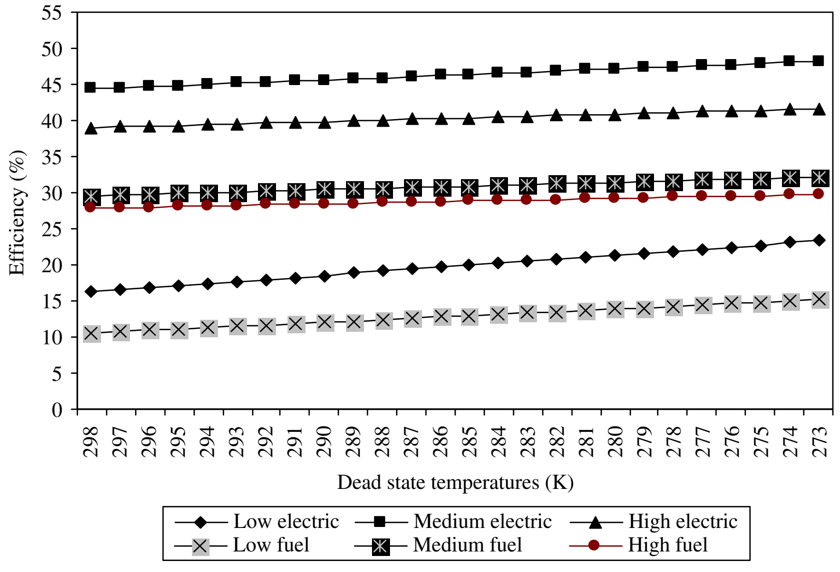


Fig. 7. Variation of exergy efficiencies for the sugar industry at various dead-state temperatures.

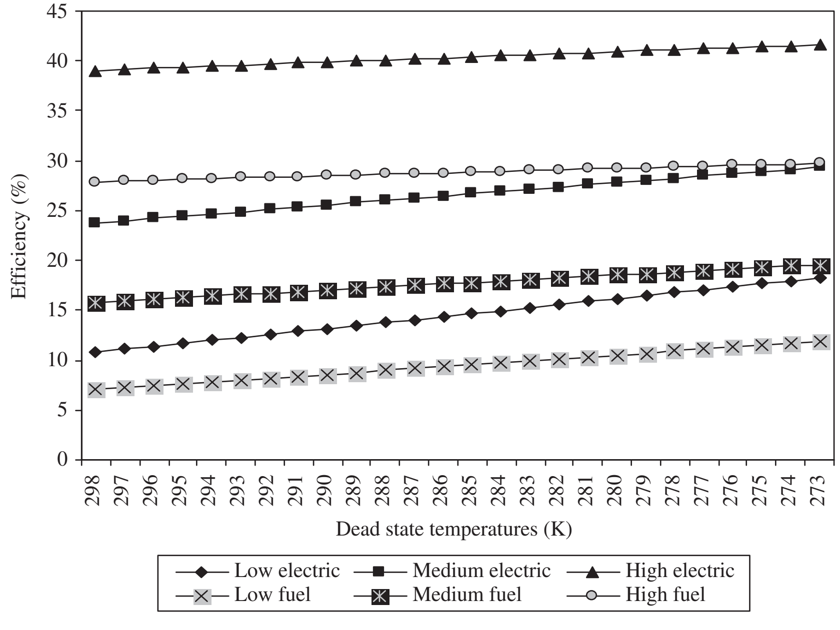


Fig. 8. Variation of energy efficiencies for the non-iron metals industry at various dead-state temperatures.

The exergy efficiency for low temperature heating is found as follows:

$$\varepsilon_{f,lh} = 6.81123 + 0.194652T - 1.92 \times 10^{-6}T^2,$$

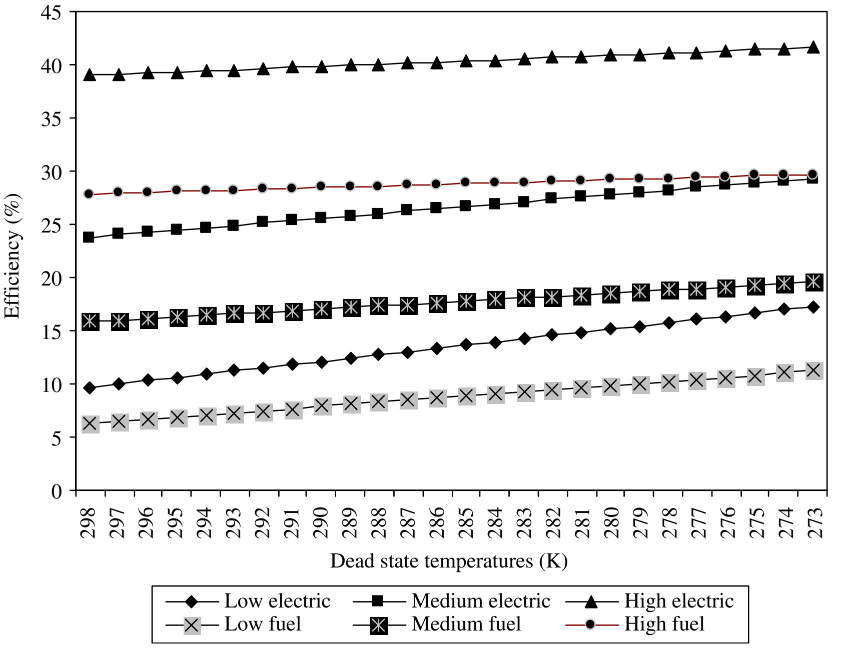


Fig. 9. Variation of exergy efficiencies for the other industries at various dead-state temperatures.

$$\begin{aligned}\varepsilon_{f,lh} &= 6.81123 + 0.194652(288) - 1.92\times10^{-6}\times(288)^2\\ &= 0.089\ (\text{or } 8.95\%).\end{aligned}$$

Similarly, the exergy efficiencies for the medium- and high-temperature heating process can be found as follows:

Medium heating ($T_p = 405\,\mathrm{K}$):

$$\begin{aligned}\varepsilon_{f,mh} &= 15.7042 + 0.148003T + 6.78\times10^{-6}T^2,\\ \varepsilon_{f,mh} &= 15.7042 + 0.148003(288) + 6.78\times10^{-6}\times(288)^2\\ &= 0.1733\ (\text{or } 17.33\%).\end{aligned}$$

High heating ($T_p = 674\,\mathrm{K}$):

$$\begin{aligned}\varepsilon_{f,hh} &= 27.8190 + 0.0742T - 9.46\times10^{-12}T^2,\\ \varepsilon_{f,hh} &= 27.8190 + 7.42\text{E-}02(288) - 9.46\times10^{-12}\times(288)^2\\ &= 0.2336\ (\text{or } 23.36\%).\end{aligned}$$

Similarly, the exergy efficiencies for fuel and electric process heating for each industry have been evaluated using the same method of calculations. The results are presented in Table 5.

Table 5
Exergy efficiency values of the Turkish industrial sector in 2003 at varying dead-state temperatures

Dead-state temperatures (K)	Iron–steel		Chemical–petrochemical		Petrochemical–feedstock		Fertilizer		Cement		Sugar		Non-iron metals		Other industry		Overall sector efficiencies	
	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)	ε_o (%)	a (%)
298	38.84	12.28	16.71	5.25	30.57	6.06	26.50	2.15	30.39	2.15	21.66	3.18	23.02	3.19	22.10	58.08	25.31	100
297	38.88	12.28	16.86	5.25	30.64	6.06	26.61	2.15	30.46	2.15	21.87	3.18	23.13	3.19	22.33	58.08	25.48	100
296	38.92	12.28	17.01	5.25	30.70	6.06	26.71	2.15	30.54	2.15	22.08	3.18	23.24	3.19	22.56	58.08	25.65	100
295	38.96	12.28	17.16	5.25	30.77	6.06	26.82	2.15	30.61	2.15	22.29	3.18	23.35	3.19	22.79	58.08	25.82	100
294	39.00	12.28	17.30	5.25	30.83	6.06	26.92	2.15	30.68	2.15	22.50	3.18	23.46	3.19	23.02	58.08	25.99	100
293	39.05	12.28	17.45	5.25	30.90	6.06	27.03	2.15	30.76	2.15	22.70	3.18	23.57	3.19	23.24	58.08	26.16	100
292	39.09	12.28	17.60	5.25	30.96	6.06	27.14	2.15	30.83	2.15	22.91	3.18	23.68	3.19	23.47	58.08	26.33	100
291	39.13	12.28	17.75	5.25	31.03	6.06	27.24	2.15	30.90	2.15	23.12	3.18	23.79	3.19	23.70	58.08	26.49	100
290	39.17	12.28	17.90	5.25	31.10	6.06	27.35	2.15	30.98	2.15	23.33	3.18	23.89	3.19	23.93	58.08	26.66	100
289	39.21	12.28	18.05	5.25	31.16	6.06	27.45	2.15	31.05	2.15	23.54	3.18	24.00	3.19	24.16	58.08	26.83	100
288	39.25	12.28	18.19	5.25	31.23	6.06	27.56	2.15	31.12	2.15	23.75	3.18	24.11	3.19	24.39	58.08	27.00	100
287	39.29	12.28	18.34	5.25	31.29	6.06	27.67	2.15	31.20	2.15	23.95	3.18	24.22	3.19	24.62	58.08	27.17	100
286	39.33	12.28	18.49	5.25	31.36	6.06	27.77	2.15	31.27	2.15	24.16	3.18	24.33	3.19	24.85	58.08	27.34	100
285	39.38	12.28	18.64	5.25	31.42	6.06	27.88	2.15	31.34	2.15	24.37	3.18	24.44	3.19	25.08	58.08	27.51	100
284	39.42	12.28	18.79	5.25	31.49	6.06	27.98	2.15	31.42	2.15	24.58	3.18	24.55	3.19	25.30	58.08	27.68	100
283	39.46	12.28	18.94	5.25	31.55	6.06	28.09	2.15	31.49	2.15	24.79	3.18	24.66	3.19	25.53	58.08	27.85	100
282	39.50	12.28	19.08	5.25	31.62	6.06	28.20	2.15	31.56	2.15	24.99	3.18	24.77	3.19	25.76	58.08	28.02	100
281	39.54	12.28	19.23	5.25	31.68	6.06	28.30	2.15	31.64	2.15	25.20	3.18	24.88	3.19	25.99	58.08	28.19	100
280	39.58	12.28	19.38	5.25	31.75	6.06	28.41	2.15	31.71	2.15	25.41	3.18	24.99	3.19	26.22	58.08	28.36	100
279	39.62	12.28	19.53	5.25	31.81	6.06	28.51	2.15	31.78	2.15	25.62	3.18	25.09	3.19	26.45	58.08	28.53	100
278	39.66	12.28	19.68	5.25	31.88	6.06	28.62	2.15	31.86	2.15	25.83	3.18	25.20	3.19	26.68	58.08	28.70	100
277	39.71	12.28	19.83	5.25	31.94	6.06	28.72	2.15	31.93	2.15	26.03	3.18	25.31	3.19	26.91	58.08	28.86	100
276	39.75	12.28	19.97	5.25	32.01	6.06	28.83	2.15	32.00	2.15	26.24	3.18	25.42	3.19	27.13	58.08	29.03	100
275	39.79	12.28	20.12	5.25	32.07	6.06	28.94	2.15	32.08	2.15	26.45	3.18	25.53	3.19	27.36	58.08	29.20	100
274	39.83	12.28	20.27	5.25	32.14	6.06	29.04	2.15	32.15	2.15	26.66	3.18	25.64	3.19	27.59	58.08	29.37	100
273	39.87	12.28	20.42	5.25	32.20	6.06	29.15	2.15	32.22	2.15	26.87	3.18	25.75	3.19	27.82	58.08	29.54	100

[a]Share of total energy in the industrial sector.

3.3. Mean process heating efficiencies for all temperature categories in each industry of the industrial sector

Prior to obtaining the overall energy and exergy efficiencies for the industrial sector, the overall heating efficiencies for each industry are evaluated. The methodology is illustrated in detail for the cement industry.

3.3.1. Mean heating energy and exergy efficiencies

A combined efficiency for the three temperature categories for electric and fossil fuel processes must be calculated in order to obtain an average for overall heating in a given industry.

The energy efficiency for electrical heating ($\eta_{h.e}$) can be evaluated as follows:

$$\eta_{e,e} = (\text{fraction in category}) \times (\text{energy efficiency}), \tag{9}$$

$$\eta_{e,h} = (10 \times 100) + (9.4 \times 90) + (80.4 \times 70),$$
$$\eta_{e,h} = 74.74\%.$$

Similarly, the exergy efficiency ($\varepsilon_{1h,e}$) is calculated as follows:

$$\varepsilon_{e,h} = (10 \times 13.77) + (9.4 \times 26) + (80.4 \times 40.90),$$
$$\varepsilon_{e,h} = 36.05\%.$$

Fossil fuel heating in the non-iron metal industry is used in all temperature categories. The energy and exergy efficiencies for fuel heating for the year 2003 are found as follows:

$$\eta_{h,f} = (13.8 \times 65) + (22.6 \times 60) + (63.6 \times 50),$$
$$\eta_{f,h} = 51.04\%,$$
$$\varepsilon_{h,f} = (13.8 \times 8.95) + (22.6 \times 17.33) + (63.6 \times 23.36),$$
$$\eta_{f,h} = 23.36\%.$$

The fraction of total energy utilized by the non-iron metal industry for electrical (E_e) and fossil fuel (E_f) is found for the year 2003 as follows:

For electrical energy:

$$E_e = \frac{\text{Electrical energy}}{\text{Total energy}}, \tag{10}$$

$$E_e = \frac{1.83}{29.20 + 1.83} = 0.05921 \text{ (or 5.9\%)}.$$

For fossil fuel energy:

$$E_f = 1.00 - 0.059 = 0.9471 \text{ (or 94.10\%)}.$$

For electrical exergy:

$$E_e = \frac{\text{Electrical exergy}}{\text{Total exergy}} = \frac{1.83}{30.92 + 1.83} = 0.559 \text{ (or 5.59\%)}.$$

For fossil fuel exergy:

$$E_f = 1.00 - 0.559 = 0.9431 \text{ (or 94.31\%)}.$$

Using the calculated energy efficiencies $\eta_{h,e}$ and $\eta_{h,f}$, and the fraction of electrical (E_e) and fossil fuel energy (E_f) used by the non-iron metal industry, the overall mean energy and exergy efficiencies for heating can be calculated as follows:

$$\eta_h = [(5.9 \times 74.74) + (94.10 \times 51.04)]/(5.9 + 94.1),$$
$$\eta_h = 52.43\%,$$
$$\varepsilon_h = [(5.59 \times 36.05) + (94.31 \times 23.36)]/(5.59 + 94.31),$$
$$\varepsilon_h = 24.40\%.$$

Following the same methodology, mean heating energy and exergy efficiencies for the other seven industries considered are determined, as shown in Table 5. The graphical representation of the mean heating energy and exergy efficiencies for the year 2003 is shown in Fig. 10.

3.3.2. *Overall efficiencies for the industrial sector*

Overall energy ($\eta_{h,o}$) and exergy ($\varepsilon_{1h,o}$) efficiencies of the industrial sector are calculated using equations:

$$\eta_{h,o} = [(a_{is}\eta_{his}) + (a_{pc} \times \eta_{hpc}) + (a_c\eta_{hc}) + \cdots + (a_{oi}\eta_{hoi})]/E_i, \tag{11a}$$

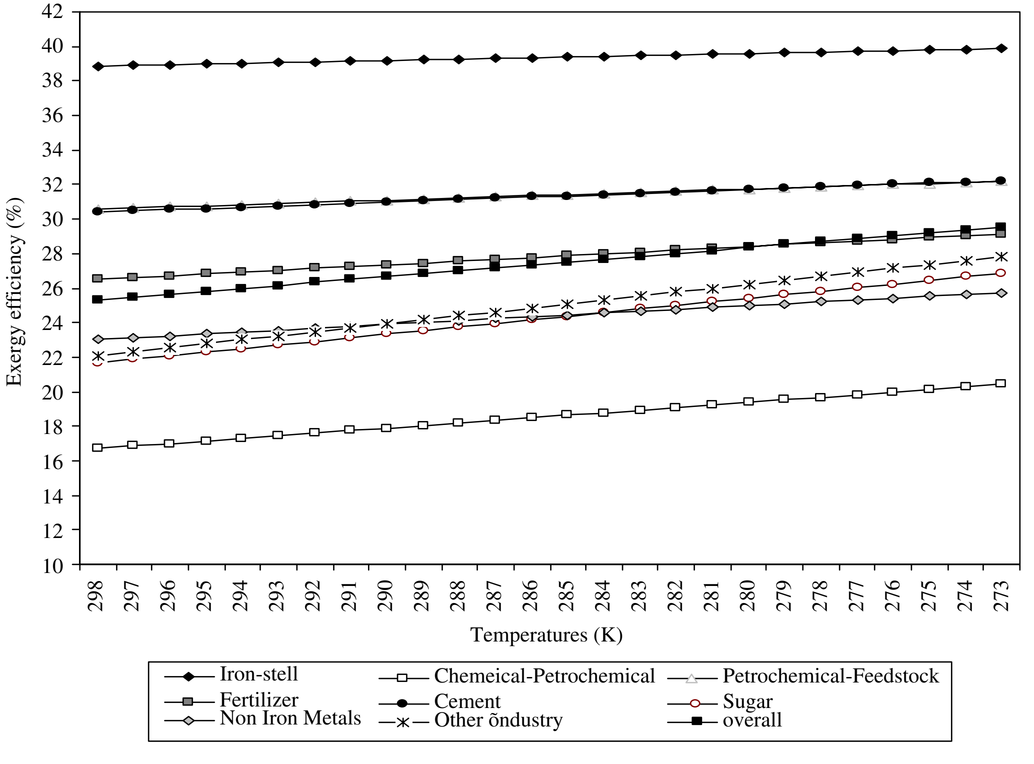


Fig. 10. Variation of exergy efficiencies of the Turkish industrial sector at various dead-state temperatures for 2003.

$$\varepsilon_{h,o} = [(a_{is}\varepsilon_{his}) + (a_{pc}\varepsilon_{hpc}) + (a_{3c}\varepsilon_{hc}) + \cdots + (a_{oi}\varepsilon_{hoi})]/E_{xi}. \quad (11b)$$

Substituting the relevant numerical values into Eqs. (11a) and (11b), we obtained $\eta_{h,o} = 65.73\%$, and $\varepsilon_{1h,o}$ from 25.3% to 29.50% in 2003 for overall industrial sector at variations dead-state temperatures. These are graphically represented in Fig. 10 for the analyzed year.

3.4. Estimation of the exergetic improvement potential in the Turkish industrial sector

Exergetic improvement potential proposed by Van Gool's [11,48] was found to be about 553 PJ at 273 K and 621 PJ at 298 in 2003 for the TIS using the following equation:

$$\mathrm{IP} = (1 - \varepsilon)(\mathrm{Ex}_{in} - \mathrm{Ex}_{out}). \quad (12)$$

4. Conclusions

This study dealt with the investigation of energy and exergy utilization efficiencies in the industrial sector at varying dead-state temperatures. A case study of Turkey was also presented for the TIS based on the actual data of 2003.

The main conclusions derived from the present study may be summarized as follows:

(a) Variations of the dead-state temperatures do not have an important impact on exergy efficiencies. Besides, this changes are displayed considerably effect on energy efficiencies because of energy efficiencies is defined as a function of requirement temperatures in system.
(b) The energy efficiency values for the TIS was found to vary from 51.95% to 80.82%, while the exergy efficiency value for that was obtained to range from 25.30% to 29.50% at the dead-state temperatures ranging from 0 to 25 °C.
(c) Energy and exergy efficiencies of the industrial sector were compared for the eight subsectors for 2003. The iron and steel subsector was the most exergy-efficient one due to the proper match of high-temperature application with high-quality energy resources.
(d) It may be concluded that the analyses reported here will provide the investigators with a better, quantitative grasp of the inefficiencies and their relative magnitudes in evaluating the energy utilization performance as well as in developing energy policies of countries.

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